Range Commanders Council

TELECOMMUNICATIONS AND TIMING GROUP

DOCUMENT 214-94

GLOSSARY OF FREQUENCY AND TIMING TERMS AND A PICTORIAL REPRESENTATION OF TERMS USED IN THE BEHAVIOR AND ANALYSES OF FREQUENCY STANDARDS

WHITE SANDS MISSILE RANGE
KWAJALEIN MISSILE RANGE
YUMA PROVING GROUND
DUGWAY PROVING GROUND
ELECTRONIC PROVING GROUND
COMBAT SYSTEMS TEST ACTIVITY

ATLANTIC FLEET WEAPONS TRAINING FACILITY
NAVAL AIR WARFARE CENTER WEAPONS DIVISION
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
NAVAL UNDERSEA WARFARE CENTER DIVISION NEWPORT

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GLOSSARY OF FREQUENCY AND TIMING TERMS AND A PICTORIAL REPRESENTATION OF TERMS USED IN THE BEHAVIOR AND ANALYSES OF FREQUENCY STANDARDS

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PREFACE

This document is a glossary of frequency and timing terms and is intended for use as a reference, so those within and outside the precision time and time interval (PTTI) field may have a common reference source for acceptable definitions and current terminology and usage of frequency and timing terms. The document should be used as a guide in preparing specifications and requirements for procurement of equipment and for other technical documents, thereby avoiding uncertainty, ambiguity, and misunderstanding of what is intended.

The expressions and definitions in Part 1, compiled by Mr. Clark Wardrip of AlliedSignal Technical Services Corporation, were obtained from numerous sources listed in the reference section at the end of this document and from private communications with individuals prominent in the PTTI field. For a more comprehensive review of topics covered, the references are an excellent source of information.

Part 2, which was contributed by Dr. John Vig of the U.S. Army Research Laboratory, expands on the definitions in the glossary. Graphs and charts show a pictorial representation of terms used in the behavior and analyses of frequency standards. The document was reviewed and approved by the Timing Committee of the Telecommunications and Timing Group (TTG), Range Commanders Council (RCC).

TABLE OF CONTENTS

GLOSSARY OF FREQUENCY AND TIMING TERMS

accuracy - the degree of conformity of a measured or calculated value to its definition or with respect to a standard reference (see **uncertainty**).

aging - the systematic change in frequency with time because of internal changes in the oscillator. For example, a 100 kHz quartz oscillator may age until its frequency becomes 100.01 kHz (see **drift**). NOTE: Aging is the frequency change with time when factors external to the oscillator such as environment and power supply are kept constant.

Allan Variance or Allan Deviation - the standard method of characterizing the frequency stability of oscillators in the time domain, both short and long term.

ambiguous time - condition of having more than one possible value. For example, if a 24-hour clock displays a time of 3 hours and 5 minutes, it is ambiguous as to the day, month, and year.

Atomic Time (TA) scale - a time scale based on atomic or molecular resonance phenomena by counting cycles of an atomic frequency source (cesium standard) rather than on the Earth's rotation.

calibration - the process of identifying and measuring time or frequency errors, offsets, or deviations of a clock/oscillator relative to an established and accepted time or reference frequency standard such as UTC U.S. Naval Observatory (USNO) or UTC National Institute of Standards and Technology (NIST) or UTC Bureau International des Poids et Mesures (BIPM).

clock - a device for maintaining and displaying time.

clock time difference - the difference between the readings of two clocks at the same instant. NOTE: To avoid confusion in sign, algebraic quantities should be given, applying the following convention. At time T of a reference time scale, let a denote the reading of the time scale A, and b the reading of the time scale B. The time scale difference is expressed by A - B = a - b at the instant T. The same convention applies to the case where A and B are clocks.

coherence of phase - exists if two periodical signals of frequency M and N resume the same phase difference after M cycles of the first and N cycles of the second, M/N being a rational number.

coordinated clock - a clock synchronized within stated limits to a spatially separated reference clock.

coordinated time scale - a time scale synchronized within stated limits to a reference time scale.

Coordinated Universal Time or Universal Time Coordinated (UTC) - a coordinated time scale, maintained by the Bureau International des Poids et Mesures (BIPM), which forms the basis of a coordinated dissemination of standard frequencies and time signals. NOTE: A UTC clock has the same rate as a Temps Atomique Internationl (TAI) clock or international atomic time clock but differs by an integral number of seconds called leap seconds. The UTC scale is adjusted by the insertion or deletion of seconds (positive or negative leap seconds) to ensure approximate agreement with UT1.

date - a unique instant of time defined in a specified time scale. NOTE: The date can be conventionally expressed in years, months, days, hours, minutes, seconds, and fractions. Also, Julian Date (JD) and Modified Julian Date (MJD) are useful dating measures (see **Julian Date** and **Modified Julian Date**).

disciplined oscillator - an oscillator with a servo loop that has its phase and frequency locked to an external reference signal with a memory of the last sampled reference frequency. If the reference frequency is temporarily unavailable, the phase and frequency of the oscillator will continue in close agreement with the extrapolated reference.

drift (frequency) - the linear (first order) component of the systematic change in frequency of an oscillator over time. Drift is due to aging plus changes in the environment and other factors external to the oscillator (see **aging**).

DUT1 - the approximate time difference between UT1 and UTC, expressed to the nearest 0.1 second. DUT1 = UT1 - UTC. NOTE: DUT1 may be regarded as a correction to be added to UTC to obtain a better approximation to UT1. The values of DUT1 are given by the International Earth Rotation Service (IERS) in integral multiples of 0.1s.

Ephemeris Time (ET) - an astronomical time scale based on the orbital motion of the earth around the sun (see **Terrestrial Time**).

epoch - signifies the beginning of an era (or event) or the reference date of a system of measurements.

error - the difference of a measured value from its true or correct value.

frequency - the rate at which a repetitive phenomenon occurs over time.

frequency analysis techniques - in the frequency domain, signals are separated into their frequency components and the power at each frequency is displayed.

- in the time domain, all frequency components of a signal are summed together.

frequency deviation - the difference between frequency values of the same signal at two different times or between the instantaneous signal frequency and the average signal frequency.

frequency difference - difference between frequency values of two different signals.

frequency drift - See **drift** and **aging**.

frequency offset - the frequency difference between the realized value and a reference frequency value. Offset is often not referenced to the nominal. For example, during irradiation testing the offset is referenced to the frequency before irradiation.

frequency shift - an intentional (or unintentional) change in frequency from a reference.

frequency stability - statistical estimate of the frequency fluctuations of a signal over a given time interval.

- long-term stability is usually measurement averages beyond 100 seconds to hours.

- short-term stability is usually measurement averages from a few tenths of a second to 100 seconds.

NOTE: Generally, there is a distinction between systematic effects such as frequency drift and stochastic frequency fluctuations. Special variances have been developed for the characterization of these fluctuations. Systematic instabilities may be caused by radiation, pressure, temperature, and humidity. Random or stochastic instabilities are typically characterized in the time domain or frequency domain. It is typically dependent on the measurement system bandwidth or on the sample time or integration time.

frequency standard - a precise frequency generator such as a rubidium, cesium, or hydrogen maser whose output is used as a frequency.

primary frequency standard - a standard whose frequency corresponds to the adopted definition of the second with its specified accuracy achieved without external calibration of the device. Currently, only the cesium frequency standard is defined as a primary standard. Rubidium gas cells, hydrogen masers, and other types of atomic standards are not, by definition, considered primary standards.

secondary frequency standard - a frequency standard which requires external calibration. For example, a crystal oscillator is considered a secondary frequency standard.

Global Positioning System (GPS) - a global, highly accurate satellite navigation system based on a constellation of 24 satellites orbiting the earth at a very high altitude. In addition to navigation, the system also provides very precise time.

GPS signals

L_1 - 1575.42 MHz
- primary navigation signal
- C/A and P codes and navigation data

L_2 - 1227.6 MHz
- second frequency provides higher accuracy ionospheric delay calibration
- P code and navigation data

L_3 - 1381.05 MHz
- global burst detector

S-Band - command channel

GPS C/A code - the standard GPS code known as the coarse/acquisition code or "civilian code." The code is a series of 1023 pseudorandom binary byphase modulations on the carrier and has a chip rate (bit transition time) of 1.023 MHz.

GPS P-code - called the precise code or "protected code" and is a series of pseudorandom, binary byphase modulations on the carrier and has a chip rate of 10.23 MHz. The P-code repeats about every 267 days. Each 1-week segment of the code is unique to a particular GPS satellite and is reset each week.

Differential GPS - the precise measurement of the position of two receivers tracking the same GPS signal. One of the receivers is a stationary reference point (precise benchmark) for position and the other is a roving receiver for determining the position of a remote location. Differential GPS is used primarily for surveying.

GPS common view - the technique involves two separated receivers, whose positions are accurately known, tracking the same GPS satellite for precise time determination. Most natural and equipment errors are eliminated using this technique.

Greenwich Mean Time (GMT) - a 24-hour system based on mean-solar time plus 12 hours at Greenwich, England. Greenwich Mean Time can be considered approximately equivalent to Coordinated Universal Time (UTC), which is broadcast from all standard time and frequency radio stations. However, GMT is now obsolete and has been replaced by UTC.

instant - a point in time.

International Atomic Time or Temps Atmomique International (TAI) - an atomic time scale based on data from a worldwide set of atomic clocks. It is the internationally agreed to time reference conforming to the definition of the second, the fundamental unit of atomic time in the International System of Units (SI). It is defined as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the Cesium 133 atom. The TAI is maintained by the Bureau International des Poids et Mesures (BIPM). Although TAI was officially introduced in January 1972, it has been available since July 1955. Its epoch was set such that TAI was in approximate agreement with UT1 on 1 January 1958 (see **second**).

Julian Day - obtained by counting days from the starting point of noon on 1 January 4713 B.C. (Julian Day zero). One way of telling what day it is with the least possible ambiguity.

Julian Date (JD) - the Julian Day number followed by the fraction of the day elapsed since the preceding noon (1200 UT).

Example: The date 1900 January (1) 0.5 day UT corresponds to JD = 2 415 020.

NOTE: The Julian Date is conventionally referred to UT1, but may be used in other contexts, if so stated.

Julian Day Number (JDN) - the number of a specific day from a continuous day count having an initial origin of 1200 UT on 1 January 4713 BC, the start of Julian day zero.

Example: The day extending from 1900 January (1) 0.5 day UT to 1900 January 1.5 days UT has the number 2 415 020.

Modified Julian Day (MJD) - equal to the Julian day. Shifted so its origin occurs at midnight on 17 November 1858. The MJD differs from the Julian date by exactly 2 400 000.5 days.

Modified Julian Date (MJD) - Julian date less 2 400 000.5

Truncated Julian Day (TJD) - the JDN 2 440 000.5 occurred on 24 May 1968 and defines the origin of the TJD time scale used in the PB5 time code. NOTE: The TJD is used by the scientific community for recording astronomical and historical events and for archival data storage and is useful in the space sciences area. The TJD has an epoch of 24 May 1968 with a repetition period (recycle time) of 10,000 days (27.379 years) and will recycle 9 October 1995. The TJD is currently equal to MJD minus 40000. TJD = MJD truncated to four digits.

leap second - an intentional time step of one second used to adjust UTC to ensure approximate agreement with UT1. An inserted second is called a positive leap second, and an omitted second is called a negative leap second. A positive leap second is presently needed about once per year.

nominal value - the ratio of a value to a reference value. NOTE: In a device that realizes a physical quantity, it is the specified value of such a quantity. It is an ideal value and free from tolerance.

normalized frequency difference - the ratio between the actual frequency (f_1) minus the nominal frequency (f_2) over the nominal frequency. Expressed as

$$\frac{\Delta f}{f} = \left(\frac{f_1 - f_2}{f_2}\right)$$

offset - the difference between the realized value and a reference value.

on time - the state of any bit (in a time code) being coincident with the Standard Time Reference (U.S. Naval Observatory or other national time standard).

phase - a measure of a fraction of the period of a repetitive phenomena, measured with respect to some distinguishable feature of the phenomena itself. In the standard-frequency and time-signal service, phase-time differences are mainly considered, for example, time differences between two identified phases of the same phenomenon or of two different phenomena.

phase jump - a sudden phase change in a signal.

phase shift - an intentional (or unintentional) change in phase from a reference.

phase deviation - the difference of the phase from a reference.

phase signature - a deliberate phase offset to identify a signal. For example, NIST's radio station WWVB broadcast is deliberately phase shifted at 10 minutes after the hour, so a person knows that WWVB is being tracked and not some other signal.

precision - the degree of mutual agreement among a series of individual measurements. Precision is often, but not necessarily, expressed by the standard deviation of the measurements.

proper time - the local time, as indicated by an ideal clock, in a relativistic sense. NOTE: Proper time is distinguished from a coordinated time which involves theory and computations. If a time scale is realized according to the proper time concept, it is called a proper time scale.

Examples: a) for proper time: the second is defined in the proper time of the cesium atom;

b) for proper time scale: a time scale is produced in a laboratory and not transmitted outside the laboratory.

reproducibility - with respect to a set of independent devices of the same design, it is the ability of these devices to produce the same value.

- with respect to a single device, it is the ability to produce the same value and to put it into operation repeatedly without adjustments.

resetability - the ability of a device to produce the same value when specified parameters are independently adjusted under stated conditions of use.

resolution - the degree to which a measurement can be determined is called the resolution of the measurement. The smallest significant difference that can be measured with a given instrument. For example, a measurement made with a time interval counter might have a resolution of 10 nanoseconds.

resolution of a time code - the smallest increment of time or least significant bit which can be defined by a time code word or subword.

second - the basic unit of time or time interval in the International System of Units (SI) which is equal to 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of Cesium 133 as defined at the 1967 Conference Generale des Poids et Mesures.

sidereal time - in general terms, the measure of time defined by the apparent diurnal motion of the vernal equinox; hence, a measure of the rotation of the Earth with respect to the reference frame that is related to the stars rather than the sun. Two types of sidereal time are used in astronomy: mean sidereal time and apparent sidereal time. One sidereal day is equal to about 23 hours, 56 minutes, and 4.090

seconds of mean solar time. Also, 366.2422 mean sidereal days equal 365.2422 mean solar days.

standard frequency - a frequency with a known relationship to a reference frequency standard. NOTE: The term standard frequency is often used for a signal whose source is from a reference standard frequency.

standard frequency or time-signal station - a station which provides a standard-frequency or time-signal emissions such as NIST's radio station WWV.

standard-frequency emission - an emission which disseminates a standard frequency at regular intervals with a specified frequency accuracy. NOTE: In Recommendation 460, the Consultative Comitè International Radio (CCIR) recommends a normalized frequency deviation of less than 1×10^{-10}. The CCIR is now known as the Interntional Telecommunications Union-Radio (ITU-R).

standard frequency satellite service - a radio communication service using earth satellites for the same purpose as those of the terrestrial standard frequency service.

standard-time-signal emission - an emission which disseminates a sequence of time signals at regular intervals with a specified accuracy, for example, NIST's radio station WWV. NOTE: In Recommendation 460, the CCIR recommends standard time-signals to be emitted within 1 ms with reference to UTC and to contain DUT1 information in a specified code.

synchronization - the process of measuring the difference in time of two time scales such as the output signals generated by two clocks. In the context of timing, synchronization means to bring two clocks or data streams into phase so that their difference is zero (seë **time scales in synchronism**).

syntonization - relative adjustment of two frequency sources with the purpose of canceling their frequency difference but not necessarily their phase difference.

stratum clocks - accuracy requirements placed on clocks in four stratum levels. Accuracy of stratum clocks refers to clock performance when the clock receives no input reference.

Stratum Clock 1 - will have an accuracy equal to or greater than 1×10^{-11}.

Stratum Clock 2 - will have or be adjustable to a minimum accuracy of 1.6×10^{-8}.

Stratum Clock 3 - will have or be adjustable to a minimum accuracy of 4.6×10^{-6}.

Stratum Clock 4 - will have or be adjustable to a minimum accuracy of 3.2×10^{-5}

Terrestrial Time (TT) - the new 1991 International Astronomical Union replacement for what was once called Ephemeris Time. On 1 January 1997, TT = TAI + 32.184 seconds, and the length of the second is chosen so that it agrees with the International Second (SI) on the geoid. The TT scale differs from the old Ephemeris Time in its conceptual definition. Practically, however, it is realized by means of International Atomic Time (TAI).

time code - a system of symbols (digital or analog) used for identifying specific instants of time. An information format used to convey time information. NOTE: Time is used to specify time of day or a measure of time interval.

time comparison - the determination of a time-scale difference.

time interval - the duration between two instants read on the same time scale.

time marker - a reference signal enabling the assignment of dates on a time scale.

time reference - the basic repetition rate chosen as the common time reference for all instrumentation (usually 1 pulse per second (pps)).

time scale - a system of unambiguous ordering of events. A time scale is meant to be stable and homogeneous.

time-scale difference - the difference between the readings of two time scales at the same instant (see **clock time difference**).

time scales in synchronism - two time scales are in synchronism when they assign the same date to an instant. NOTE: If the time scales are produced in spatially separated locations, the propagation time of transmitted time signals and relativistic effects, including the reference coordinate frame, are to be taken into account.

time-scale reading - the value read on a time scale at a specific instant. NOTE: The reading of a time scale should be qualified by giving the time scale a name.

time-scale unit - the defining basic time interval in a time scale. NOTE: This unit is different from the realized time scale unit.

time-signal satellite service - a radio communication service using Earth satellites for the same purpose as those of the time-signal service.

time standard - device used for the realization of the time unit.

- continuously operating device used for the realization of a time scale in accordance with the definition of the second and with an appropriately chosen origin.

time step - a discontinuity in a time scale at some instant. NOTE: A step is positive (+) if the time scale reading is increased and negative (-) if the reading is decreased at that instant.

uncertainty - the limits of the confidence interval of a measured or calculated quantity. NOTE: The probability of the confidence limits should be specified, preferably by the 1 sigma value.

Universal Time (UT) Family - Universal Time (UT) is the general designation of time scales based on the rotation of the Earth. In applications in which a precision of a few tenths of a second cannot be tolerated, it is necessary to specify the form of UT such as UT1 which is directly related to polar motion and is proportional to the rotation of the Earth in space. The UT1 is further corrected empirically for annual and semiannual variations in the rotation rate of the earth to obtain UT2.

- Universal Time is the mean solar time of the prime meridian plus 12 hours, determined by measuring the angular position of the Earth about its axis. The UT is sometimes designated GMT, but this designation should be avoided. Communicators use the designation (Z) or (Zulu). Timekeepers should use UTC of the national standard, for example, UTC(USNO) rather than GMT.

- Mean Solar Time is simply apparent solar time corrected for the effects of orbital eccentricity and the tilt of the Earth's axis relative to the ecliptic plane; that is, corrected by the equation of time which is defined as the hour angle of the true Sun minus the hour angle of the mean Sun.

UTO - UTO measures UT with respect to the observer's meridian (position on earth) which varies because of polar motion.

TIME CODE DEFINITIONS

binary coded decimal - a numbering system which uses decimal digits encoded in a binary representation.

binary number system - a numbering system which has two as its base and uses two symbols, usually denoted by 0 and 1.

bit - an abbreviation of binary or binary coded decimal digits of which a word or subword is composed.

bit transition time - the time required for a bit in the time code or subword to change from one logic level to the next such as a logic 0 to a logic 1 or vice versa.

identification bits (ID) - bits with a fixed state (logic level) used for time-code identification and other information.

inhibit/read bit - a bit generated with the time code which can be used to prohibit a user from reading the code during the time code update.

parity bit - confidence bits derived from and generated with the bits in the time-code word or subword.

subword - a subdivision of the time-code word containing only one type of time unit such as days, milliseconds, or microseconds.

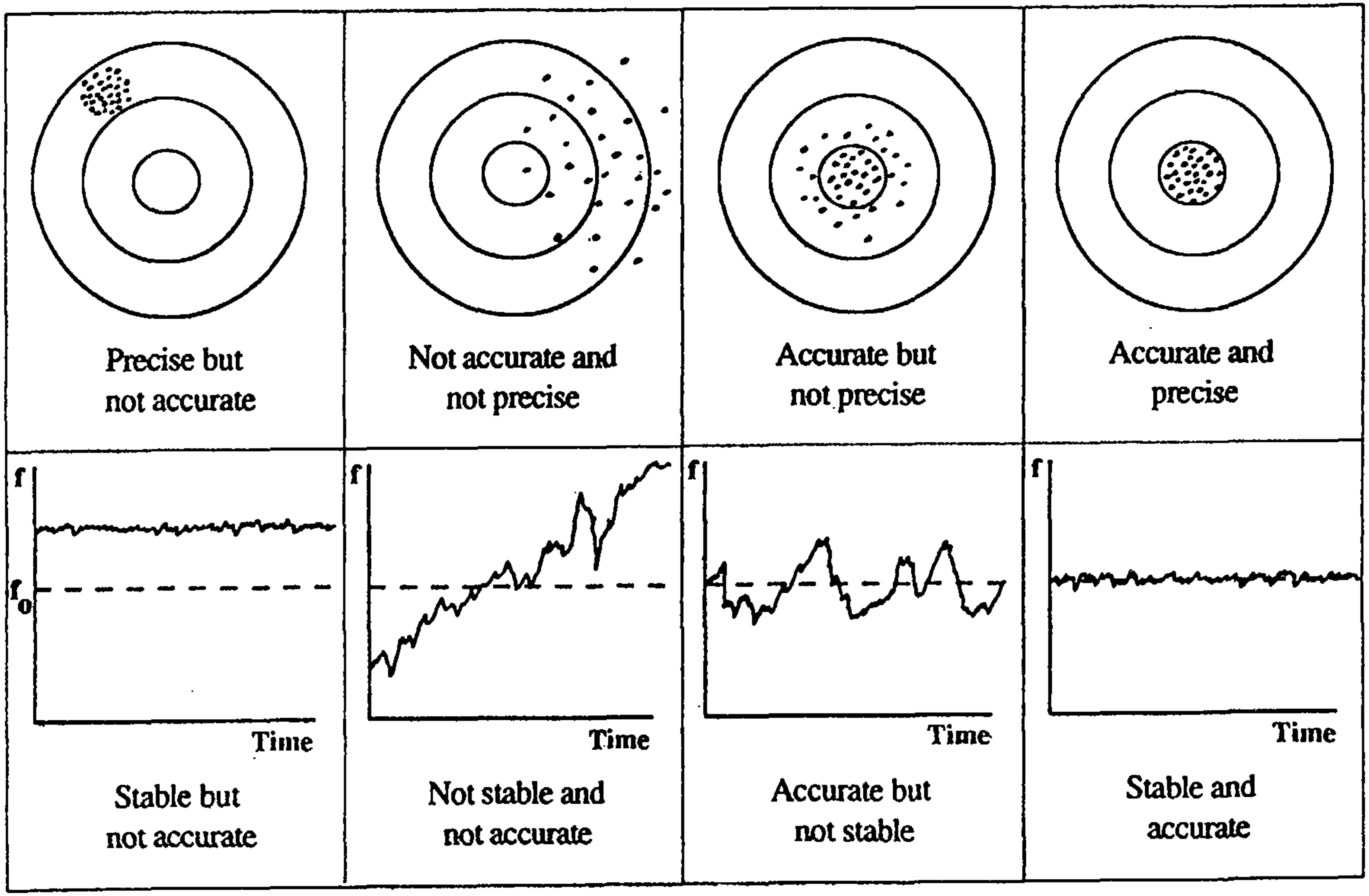
time-code word - a specific set of time-code symbols which identify one instant of time. A time-code word may be subdivided into subwords.

PICTORIAL REPRESENTATION OF TERMS USED IN THE BEHAVIOR AND ANALYSES OF FREQUENCY STANDARDS

The Units of Stability in Perspective

- What is one part in 10^{10} ? (As in 1×10^{-10}/day aging.)
  - ~1/2 cm out of the circumference of the earth.
  - ~1/4 second per human lifetime (~80 years).
- What is -170 dB? (As in -170 dBc/Hz phase noise.)
  - -170 dB = 1 part in 10^{17} $\approx$ thickness of a sheet of paper out of total distance traveled by all the cars in the world in a day.

Accuracy, Precision and Stability



Influences on Oscillator Frequency

- **Time**
  - Short term (noise)
  - Intermediate term (e.g., due to oven fluctuations)
  - Long term (aging)

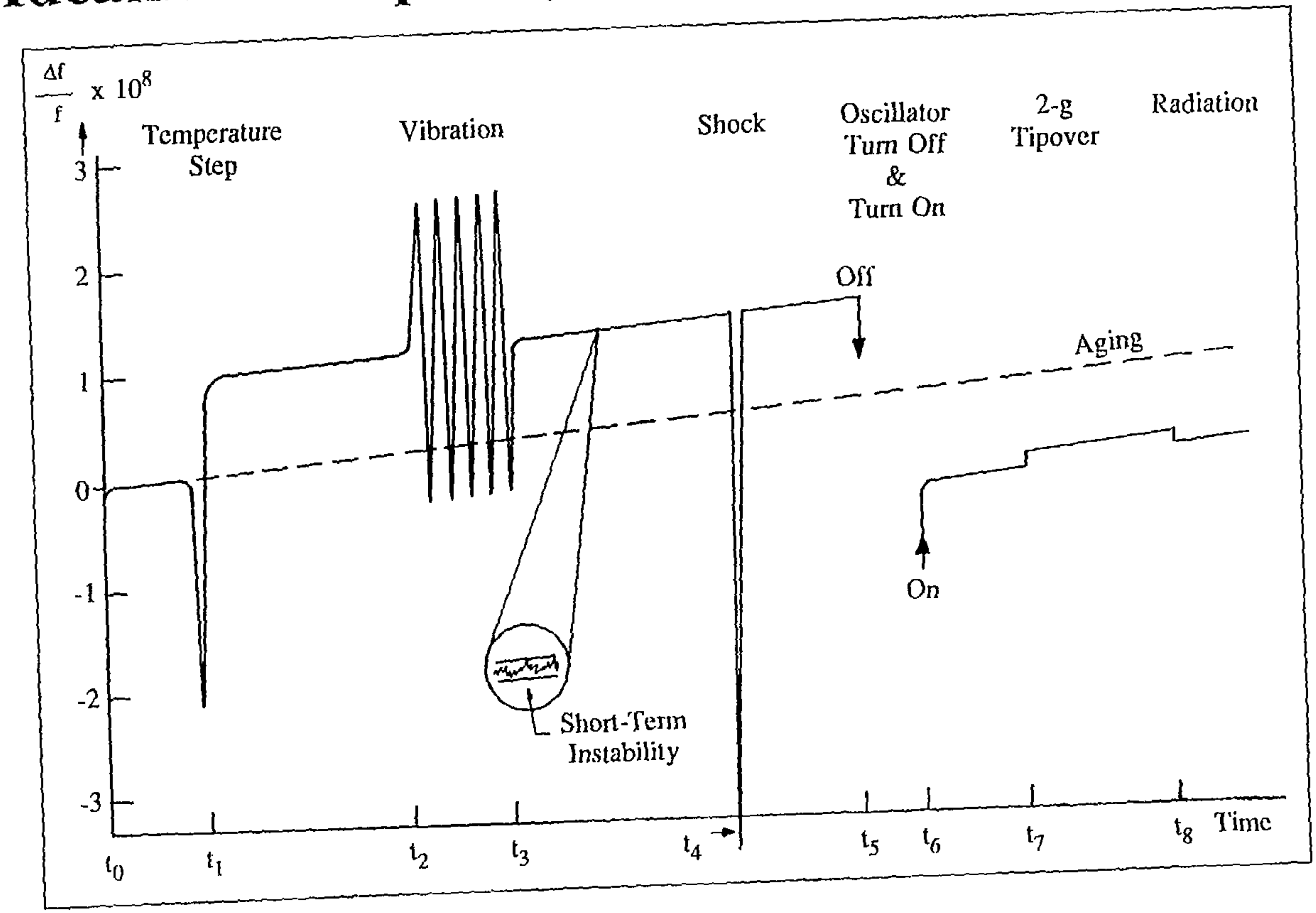
- **Temperature**
  - Static frequency vs. temperature
  - Dynamic frequency vs. temperature (warmup, thermal shock)
  - Thermal history ("hysteresis," "retrace")

- **Acceleration**
  - Gravity (2g tipover)
  - Vibration
  - Acoustic noise
  - Shock

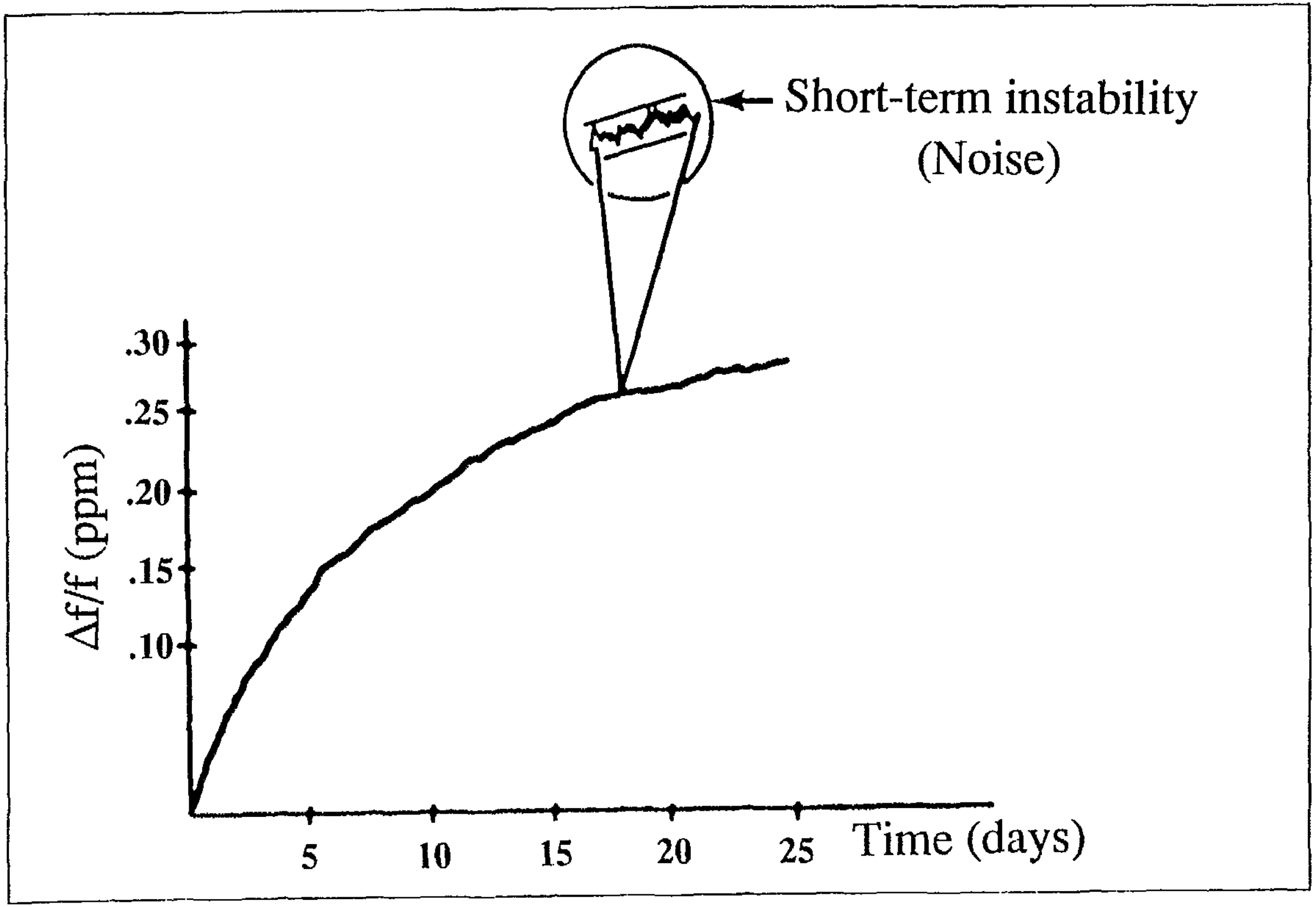
- **Ionizing radiation**
  - Steady state
  - Pulsed
  - Photons (X-rays, γ-rays)
  - Particles (neutrons, protons, electrons)

- **Other**
  - Power supply voltage
  - Atmospheric pressure (altitude)
  - Humidity
  - Magnetic field
  - Load impedance

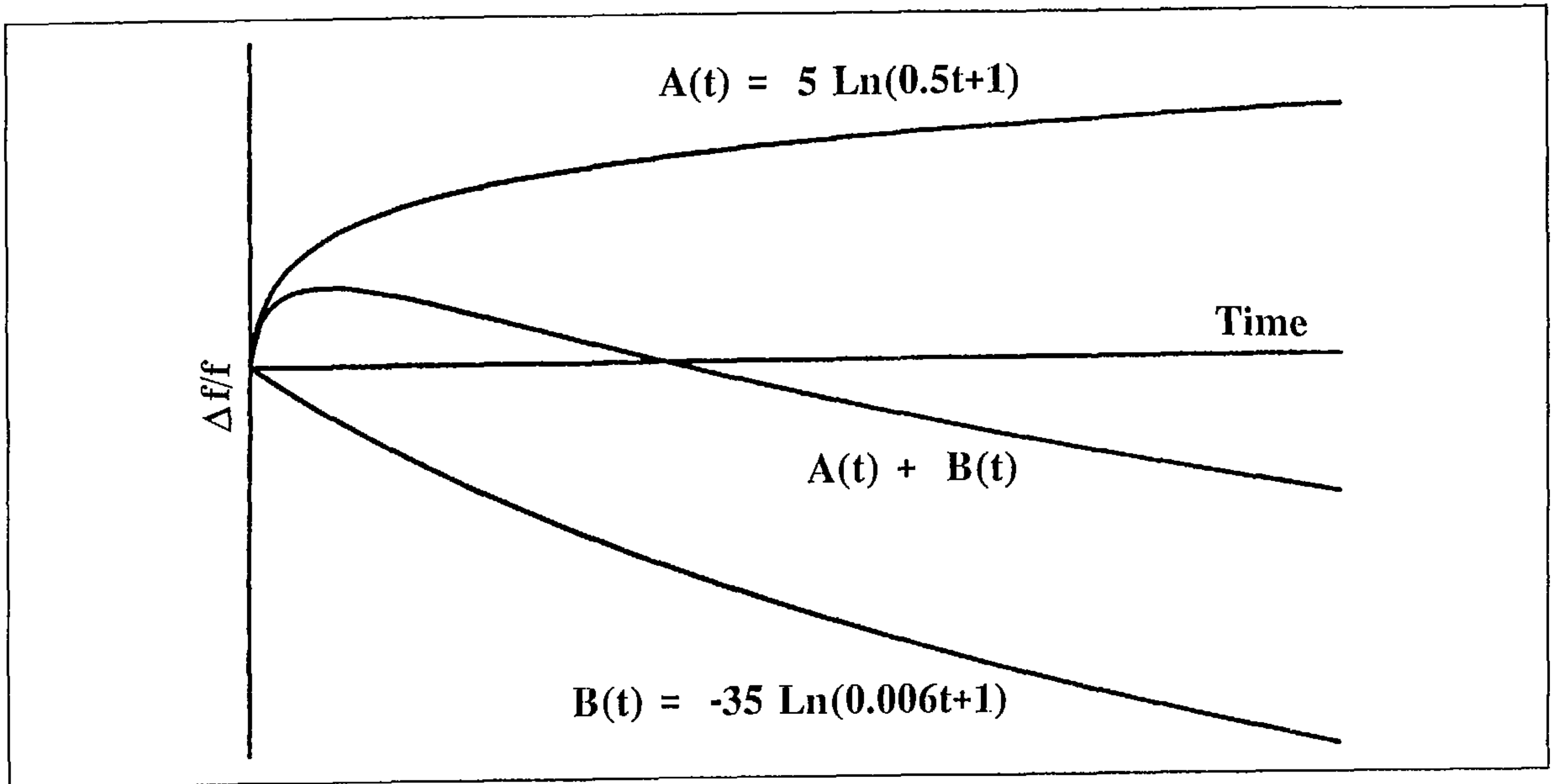
Idealized Frequency-Time-Influence Behavior



Aging and Short-Term Stability



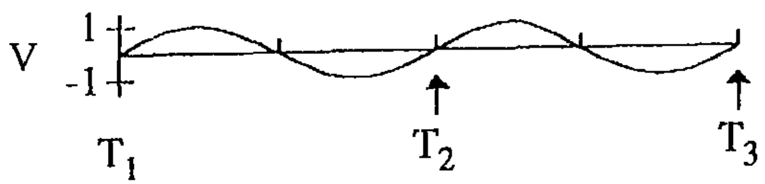
Typical Aging Behaviors

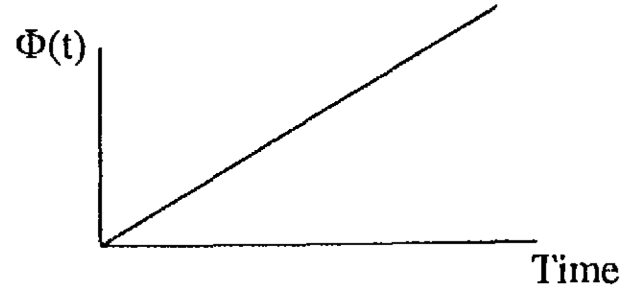


Aging can be positive or negative. Occasionally, a reversal of aging direction is observed. The above (computer generated) curves illustrate the three types of aging behaviors. The curve showing the reversal is the sum of the other two curves. Reversal indicates the presence of at least two aging mechanisms.

Short Term Instability (Noise)

Stable Frequency (Ideal Oscillator)

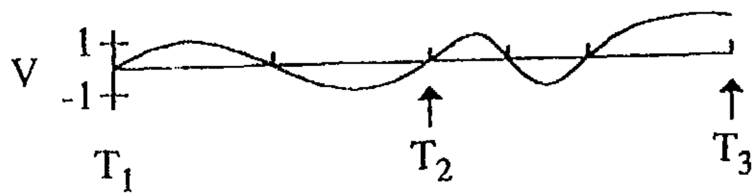


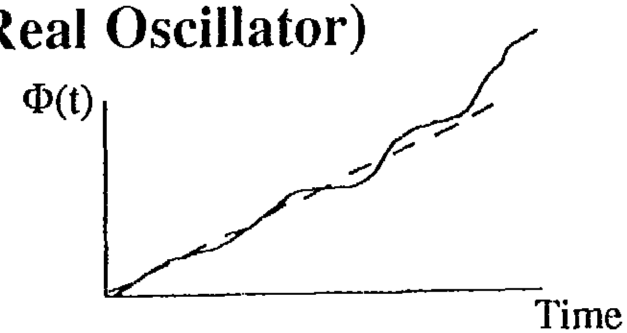


$V(t) = V_o \sin(2\pi\nu_o t)$

$\Phi(t) = 2\pi\nu_o t$

Unstable Frequency (Real Oscillator)





$V(t) = [V_o + \varepsilon(t)] \sin[2\pi\nu_o t + \phi(t)]$

$\Phi(t) = 2\pi\nu_o t + \phi(t)$

Instantaneous frequency, $\nu(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = \nu_o + \frac{1}{2\pi}\frac{d\phi(t)}{dt}$

$V(t)$ = Oscillator output voltage, V_o = Nominal peak voltage amplitude

$\varepsilon(t)$ = Amplitude noise, ν_o = Nominal (or "carrier") frequency

$\Phi(t)$ = Instantaneous phase, and $\phi(t)$ = Deviation of phase from nominal (i.e., the ideal)

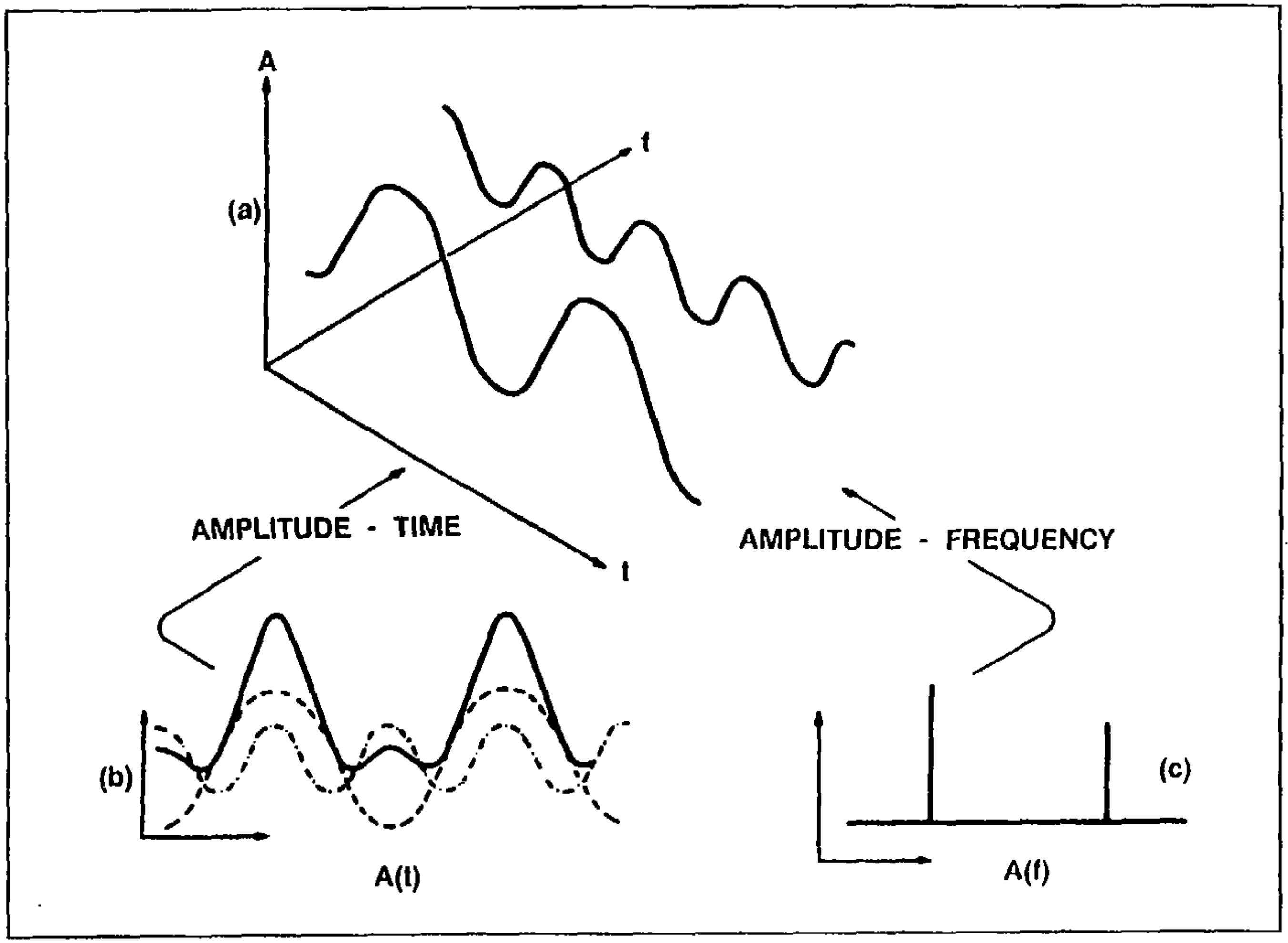
Impacts of Oscillator Noise

- Limits the ability to determine the current state and the predictability of precision oscillators
- Limits syntonization and synchronization accuracy
- Limits receivers' useful dynamic range, channel spacing, and selectivity; can limit jamming resistance
- Limits radar performance (especially Doppler radar's)
- Causes timing errors [$\sim\tau\sigma_y(\tau)$]
- Causes bit errors in digital communication systems
- Limits number of communication system users, as noise from transmitters interfere with receivers in nearby channels
- Limits navigation accuracy
- Limits ability to lock to narrow-linewidth (atomic) resonances
- Can cause loss of lock; can limit acquisition/reacquisition capability in phase-locked-loop systems

Causes of Short Term Instabilities

- Temperature fluctuations - thermal transient effects
  - activity dips at oven set-point
- Johnson noise (thermally induced charge fluctuations, i.e., "thermal emf" in resistive elements)
- Acoustic losses (i.e., Q)
- Random vibration
- Fluctuations in the number of adsorbed molecules
- Stress relief, fluctuations at interfaces (quartz, electrode, mount, bond)
- Noise due to oscillator circuitry (active and passive components)
- Shot noise in atomic frequency standards
- ? ? ?

Time Domain - Frequency Domain



Example (a) shows a sine wave and its second harmonic. A signal consisting of the sum of the two waves is shown in the time domain (b), and in the frequency domain (c). In the time domain, all frequency components are summed together. In the frequency domain, signals are separated into their frequency components and the power level at each frequency is displayed.

Short-Term Stability Measures

Measure	Symbol
Two-sample deviation (square-root of Allan variance)	$\sigma_y(\tau)$*
Spectral density of phase deviations	$S_\phi(f)$
Spectral density of fractional frequency deviations	$S_y(f)$
Phase noise	$\mathcal{L}(f)$*
* Most frequently found on oscillator specification sheets	

$f^2 S_\phi(f) = \nu^2 S_y(f)$; $\mathcal{L}(f) \equiv 1/2[S_\phi(f)]$ (per IEEE Std.1139-1988),

and $$\sigma_y^2(\tau) = \frac{2}{(\pi\nu\tau)^2}\int_0^\infty S_\phi(f)\,\sin^4(\pi f\tau)\,df$$

where τ = averaging time, f = Fourier frequency, or "frequency from the carrier", and ν = carrier frequency.

Allan Variance

The **two-sample deviation**, or square-root of the "**Allan variance,**" is the standard method of describing the short-term stability of oscillators in the time domain. It is usually denoted by $\sigma_y(\tau)$,

where $$\sigma_y^2(\tau) = \frac{1}{2} \langle (y_{k+1} - y_k)^2 \rangle .$$

The fractional frequencies, $y = \frac{\Delta f}{f}$, are measured over a time interval, τ; $(y_{k+1} - y_k)$ are the differences between pairs of successive measurements of y, and, ideally, < > denotes a time average of an infinite number of $(y_{k+1} - y_k)^2$. A good estimate can be obtained by a limited number, m, of measurements ($m \geq 100$). $\sigma_y(\tau)$ generally denotes $\sqrt{\sigma_y^2(\tau, m)}$, i.e.,

$$\sigma_y^2(\tau) = \sigma_y^2(\tau, m) = \frac{1}{m} \sum_{j=1}^{m} \frac{1}{2} (y_{k+1} - y_k)_j^2$$

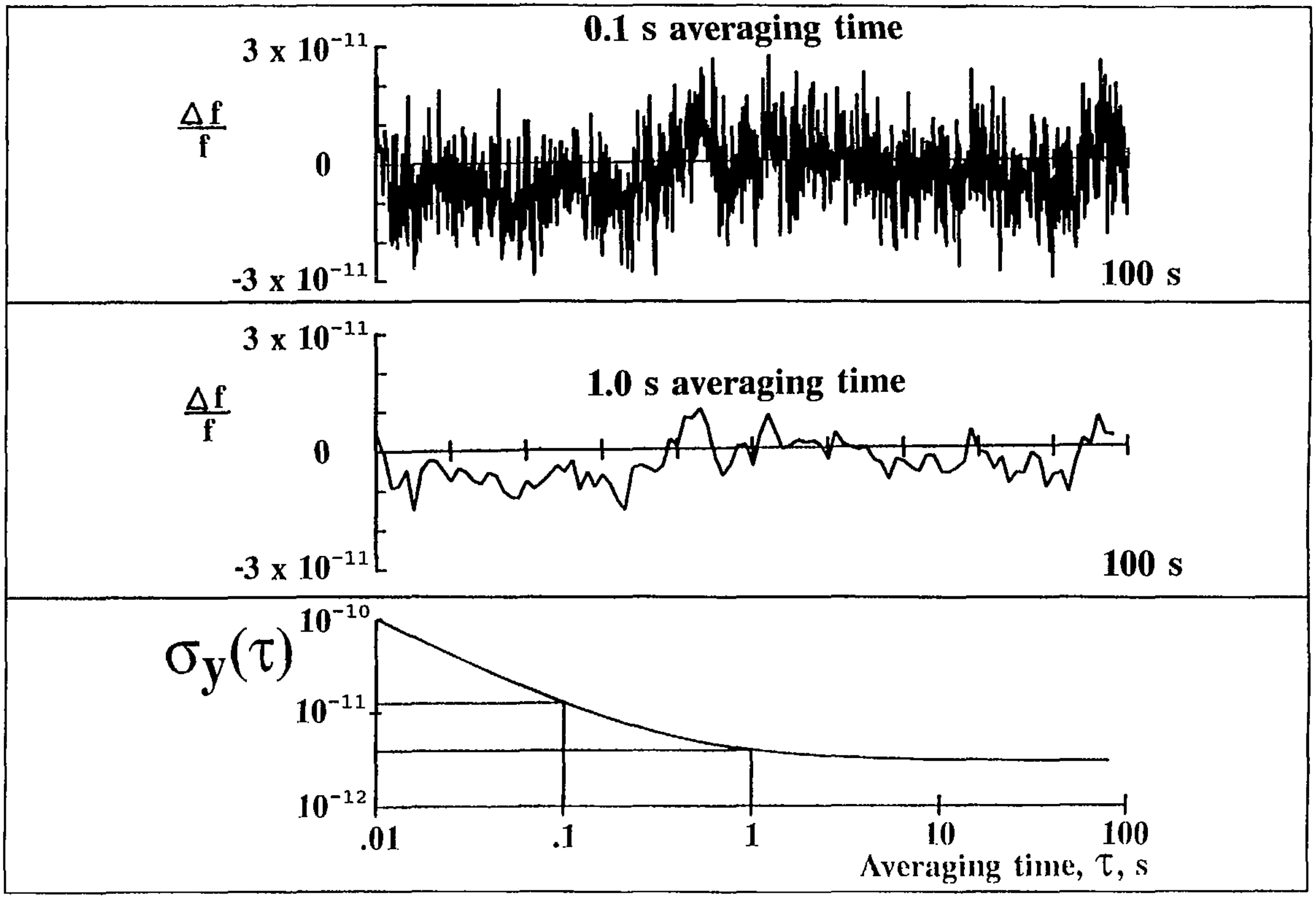
Why Allan Variance?

- **Classical variance:** $\sigma^2 = \frac{1}{m-1} \Sigma (y_i - \bar{y})^2$,

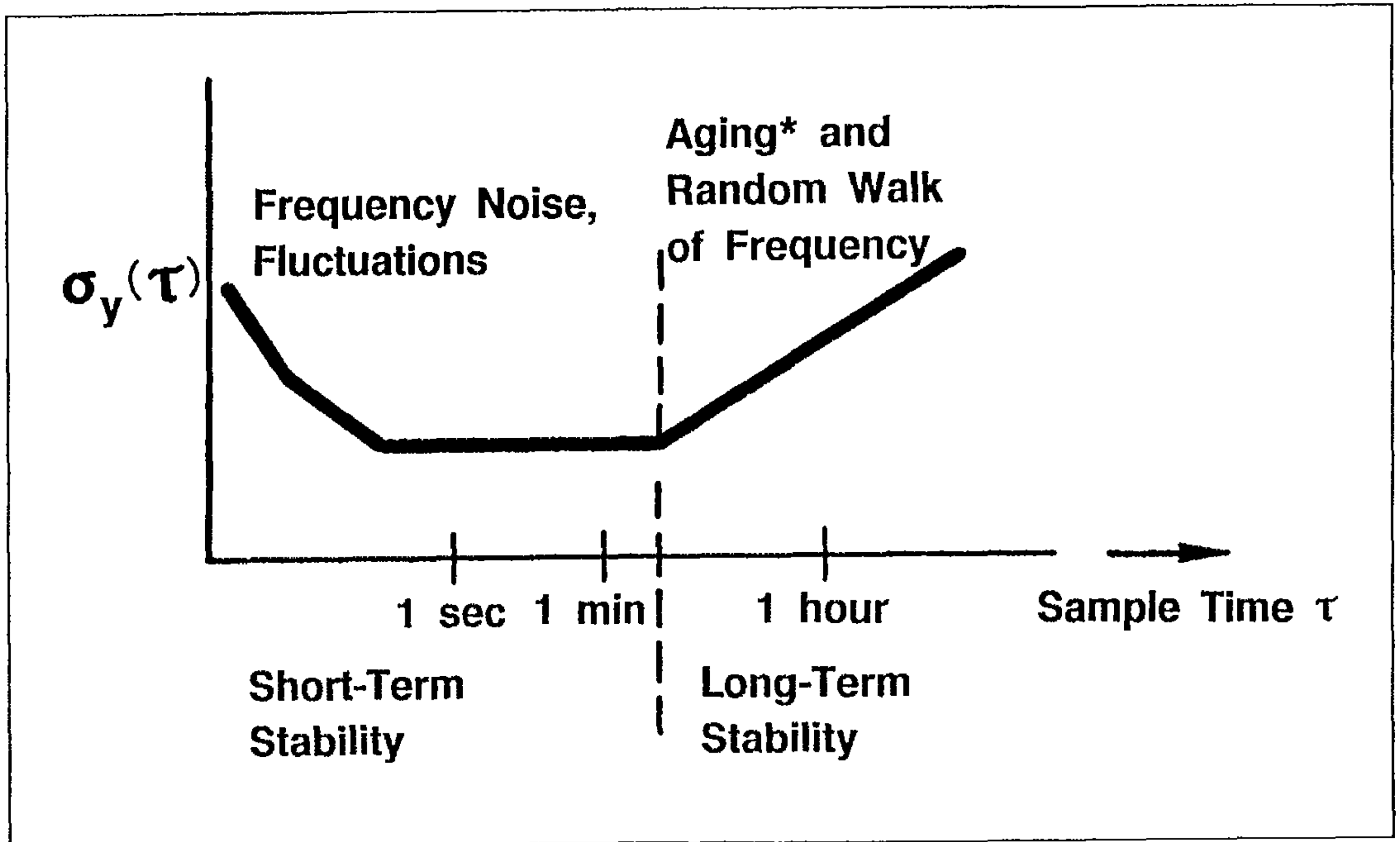
  diverges for commonly observed noise processes, such as random walk, i.e., the variance increases with increasing number of data points.

- **Allan variance:**
  - Converges for all noise processes observed in precision oscillators.
  - Has straightforward relationship to power law spectral density types.
  - Is easy to compute.
  - Is faster and more accurate in estimating noise processes than the Fast Fourier Transform.

Frequency Noise and $\sigma_y(\tau)$



Time Domain Stability



*For $\sigma_y(\tau)$ to be a proper measure of random frequency fluctuations, aging must be properly subtracted from the data at long τ's.

Spectral Densities

$$V(t) = [V_0 + \varepsilon(t)] \sin [2\pi\nu_0 t + \phi(t)]$$

In the frequency domain, due to the "phase noise", $\phi(t)$, some of the power is at frequencies other than ν_0. The stabilities are characterized by "spectral densities." The spectral density $S_V(f)$, the mean-square voltage $\langle V^2(t) \rangle$ in a unit bandwidth centered at f, is not a good measure of frequency stability because both $\varepsilon(t)$ and $\phi(t)$ contribute to it, and because it is not uniquely related to frequency fluctuations (although $\varepsilon(t)$ is usually negligible in precision frequency sources.)

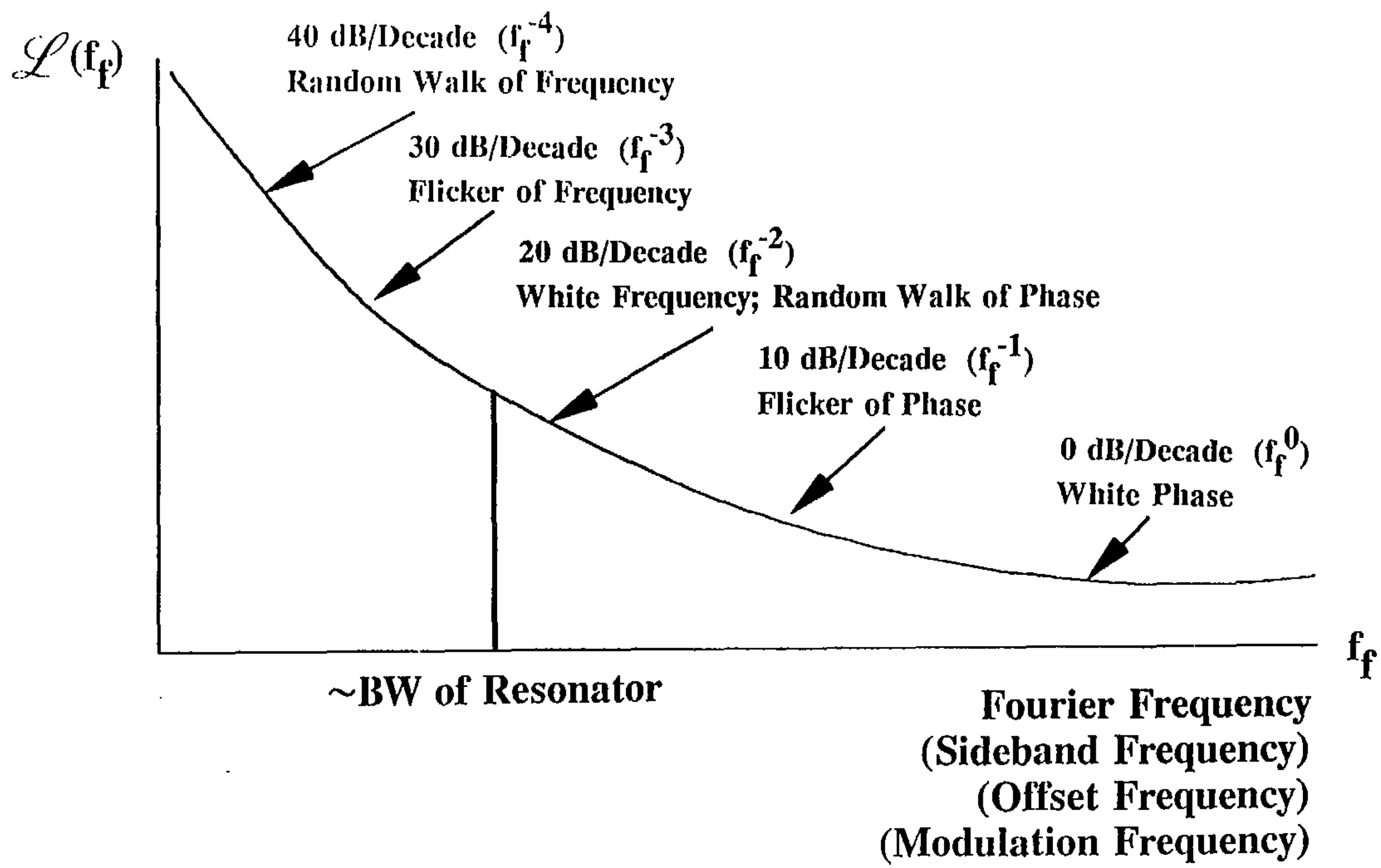
The spectral densities of phase and fractional-frequency fluctuations, $S_\phi(f)$ and $S_y(f)$, respectively, are used to characterize stabilities in the frequency domain. The spectral density $S_g(f)$ of a quantity g(t) is the mean square value of g(t) in a unit bandwidth centered at f. Moreover, the RMS value of g^2 in bandwidth BW is given by $g^2_{RMS}(t) = \int_{BW} S_g(f)\, df$.

Pictures of Noise

Plot of z(t) vs. t	$S_z(f) = h_\alpha f^\alpha$	Noise name
	$\alpha = 0$	White
	$\alpha = -1$	Flicker
	$\alpha = -2$	Random walk
	$\alpha = -3$	

Plots show fluctuations of a quantity z(t), which can be, e.g., the output of a counter (Δf vs. t) or of a phase detector ($\phi[t]$ vs. t). The plots show simulated time-domain behaviors corresponding to the most common (power-law) spectral densities; h_α is an amplitude coefficient. Note: since $S_{\Delta f} = f^2 S_\phi$, e.g. white frequency and random walk of phase are equivalent.

Types of Phase Noise



Precision Frequency Standards

- **Quartz crystal resonator-based** ($f \sim 5$ MHz, $Q \sim 10^6$)
- **Atomic resonator-based**
  - Rubidium^{87} ($f_0 = 6.8$ GHz, $Q \sim 10^7$)
  - Cesium^{133} ($f_0 = 9.2$ GHz, $Q \sim 10^8$)
  - Hydrogen ($f_0 = 1.4$ GHz, $Q \sim 10^9$)
  - Trapped ions ($f_0 > 10$ GHz, $Q > 10^{11}$)

Atomic Frequency Standard Basic Concepts

When an atomic system changes energy from an excited state to a lower energy state, a photon is emitted. The photon frequency ν is given by Planck's law

$$\nu = \frac{E_2 - E_1}{h}$$

where E_2 and E_1 are the energies of the upper and lower states, respectively, and h is Planck's constant. An atomic frequency standard produces an output signal the frequency of which is determined by this intrinsic frequency rather than some property of a bulk material (as it is in quartz oscillators).

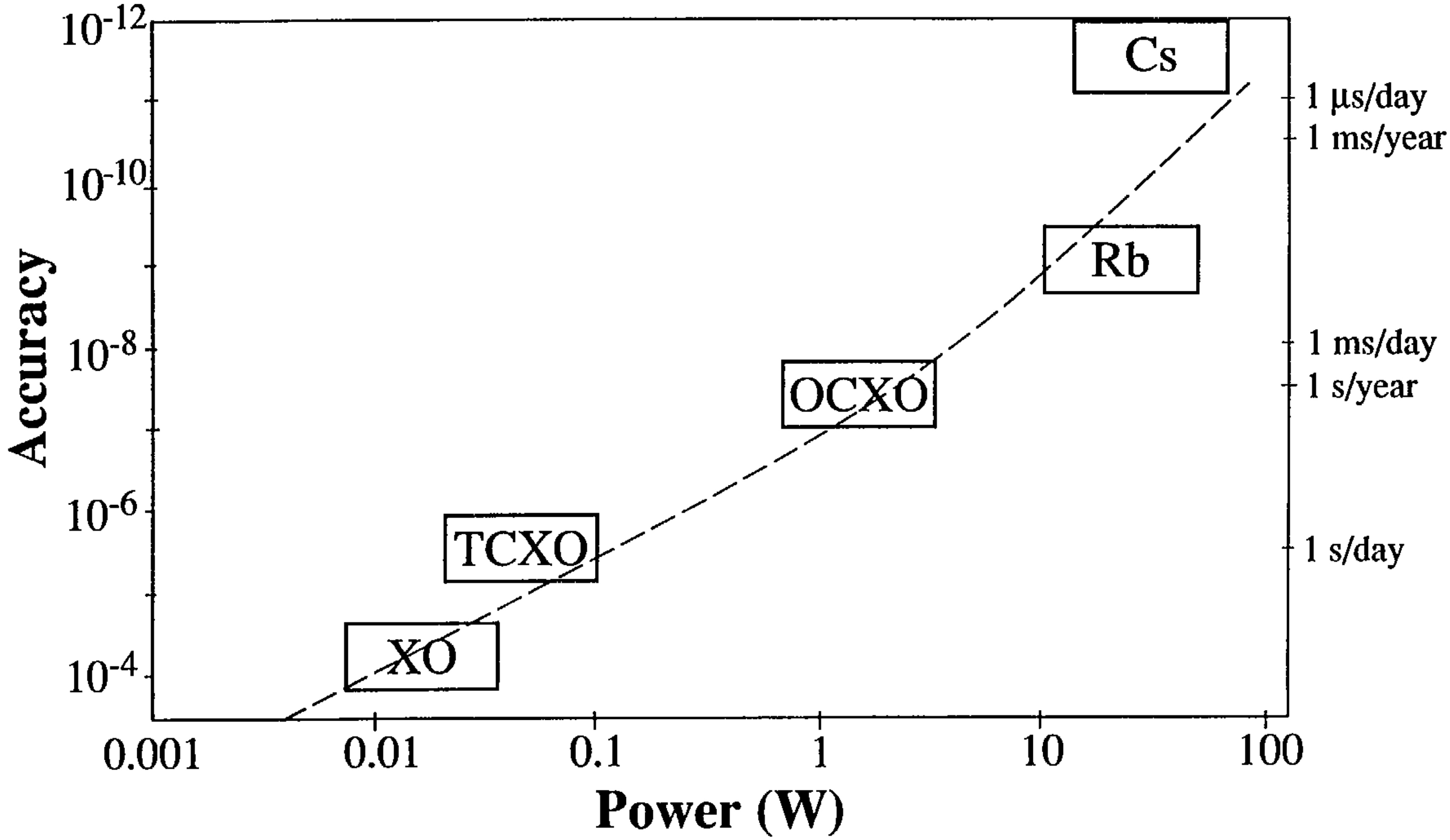
The properties of isolated atoms at rest, and in free space, would not change with space and time. Therefore, the frequency of an ideal atomic frequency standard would not change with time or with changes in the environment. Unfortunately, in real atomic frequency standards: 1) the atoms are moving at thermal velocities, 2) the atoms are not isolated but experience collisions and electric and magnetic fields, and 3) some of the components needed for producing and observing the atomic transitions contribute to instabilities.

Oscillator Comparison

	Quartz Oscillators			Atomic Oscillators		
	TCXO	MCXO	OCXO	Rubidium	RbXO	Cesium
Accuracy* (per year)	2×10^{-6}	5×10^{-8}	1×10^{-8}	5×10^{-10}	7×10^{-10}	2×10^{-11}
Aging/Year	5×10^{-7}	2×10^{-8}	6×10^{-9}	2×10^{-10}	2×10^{-10}	0
Temp. Stab. (range, °C)	5×10^{-7} (-55 to +85)	2×10^{-8} (-55 to +85)	1×10^{-9} (-55 to +85)	3×10^{-10} (-55 to +68)	5×10^{-10} (-55 to +85)	2×10^{-11} (-28 to +65)
Stability, $\sigma_y(\tau)$ ($\tau = 1$ s)	1×10^{-9}	1×10^{-10}	1×10^{-12}	3×10^{-11}	5×10^{-12}	5×10^{-11}
Size (cm^3)	10	50	20-200	800	1200	6000
Warmup Time (min)	0.1 (to 1×10^{-6})	0.1 (to 2×10^{-8})	4 (to 1×10^{-8})	3 (to 5×10^{-10})	3 (to 5×10^{-10})	20 (to 2×10^{-11})
Power (W) (at lowest temp.)	0.05	0.04	0.25 - 4	20	0.35	30
Price (~$)	100	1,000	2,000	8,000	10,000	40,000

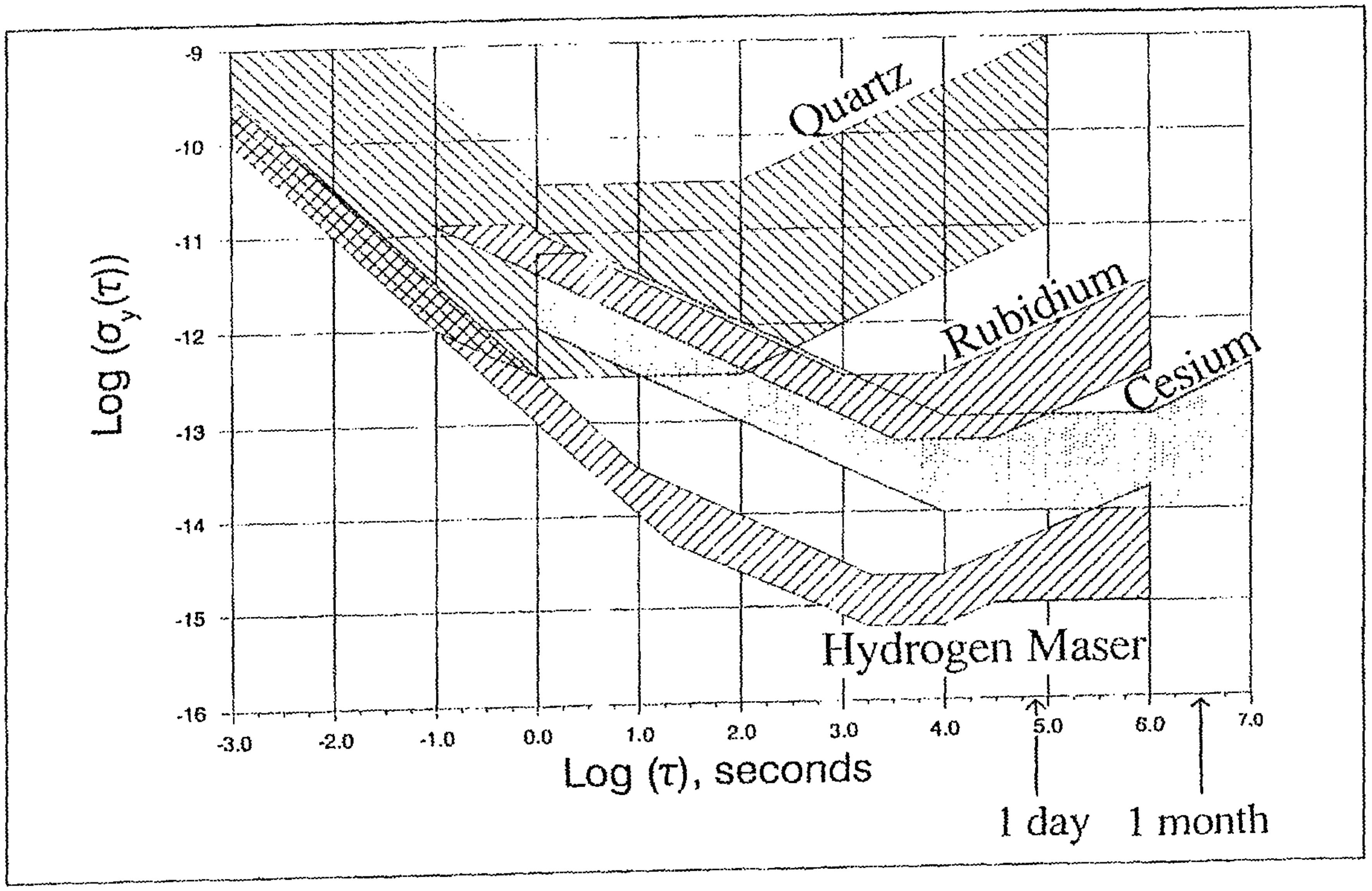
* Including environmental effects (note that the temperature ranges for Rb and Cs are narrower than for quartz).

Accuracy vs. Power-Requirement*

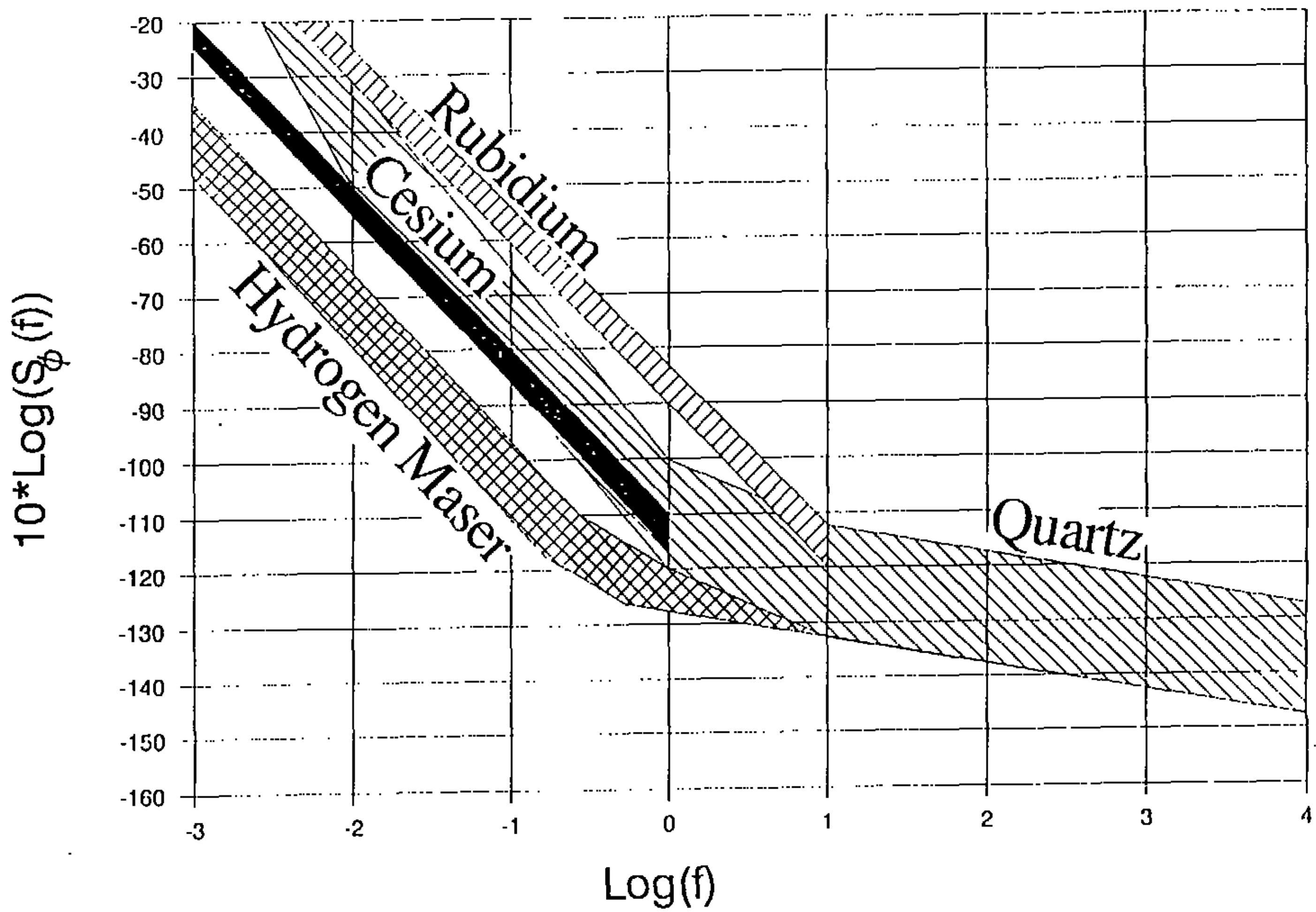


* Accuracy **vs. size**, and accuracy **vs. cost** have similar relationships.

Stability Ranges of Various Frequency Standards



Phase Instabilities of Various Frequency Standards



Typical One-sided Spectral Density of Phase Deviation vs. Offset Frequency, for Various Standards, Calculated at 5 MHz.

Oscillator Selection Considerations

- Frequency accuracy or reproducibility requirement
- Recalibration interval
- Environmental extremes
- Power availability - must it operate from batteries?
- Allowable warmup time
- Short term stability (phase noise) requirements
- Size and weight constraints
- Cost to be minimized - acquisition or life cycle cost

Oscillator Acronyms

- **XO**............... Crystal Oscillator
- **VCXO**..........Voltage Controlled Crystal Oscillator
- **OCXO**..........Oven Controlled Crystal Oscillator
- **TCXO**..........Temperature Compensated Crystal Oscillator
- **TCVCXO**.....Temperature Compensated/Voltage Controlled Crystal Oscillator
- **OCVCXO**....Oven Controlled/Voltage Controlled Crystal Oscillator
- **MCXO**.........Microcomputer Compensated Crystal Oscillator
- **RbXO**......... Rubidium-Crystal Oscillator

Crystal Oscillator Categories

The three categories, based on the method of dealing with the crystal unit's frequency vs. temperature characteristic, are:

- **XO, crystal oscillator,** which does not contain means for reducing the crystal's f vs. T characteristic (also called PXO - packaged crystal oscillator).
- **TCXO, temperature compensated crystal oscillator**, in which the output signal from a temperature sensor (thermistor) is used to generate a correction voltage that is applied to a voltage-variable reactance (varactor) in the crystal network. The reactance variations compensate for the crystal's f vs. T characteristic. Analog TCXO's can provide about a 20X improvement over the crystal's f vs. T variation.
- **OCXO, oven controlled crystal oscillator**, in which the crystal and other temperature sensitive components are in a stable oven which is adjusted to the temperature where the crystal's f vs. T has zero slope. OCXO's can provide a >1000X improvement over the crystal's f vs. T variation.

Hierarchy of Oscillators

Oscillator Type*	Accuracy**	Typical Applications
• Crystal oscillator (XO)	10^{-5} to 10^{-4}	Computer timing
• Temperature compensated crystal oscillator (TCXO)	10^{-6}	Frequency control in tactical radios
• Microcomputer compensated crystal oscillator (MCXO)	10^{-8} to 10^{-7}	Spread spectrum system clock
• Oven controlled crystal oscillator (OCXO)	10^{-8}	Navigation system clock & frequency standard, MTI radar
• Small atomic frequency standard (Rb, RbXO)	10^{-9}	C^3 satellite terminals, bistatic & multistatic radar
• High performance atomic standard (Cs)	10^{-12} to 10^{-11}	Strategic C^3, EW

*Sizes range from < 5 cm^3 for clock oscillators to > 30 liters for Cs standards. Costs range from < $5 for clock oscillators to > $40,000 for Cs standards.

**Including the effects of military environments and one year of aging.

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